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Method and apparatus for heating melts

Description

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The invention relates to a method and an apparatus for heating melts, in particular to a method and apparatus for conductively heating melts.

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The melting of glasses or glass-ceramics in conventional tanks that are known from the prior art is generally restricted to melting temperatures of 1 600°C to at most 1 650°C. The service life of the tanks is very greatly restricted even at melting temperatures of 1 700°C.

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The heating of the glass melt in conventional tanks is usually effected by oil or gas burners located in the top part of the furnace. In this case, the heat is introduced into the glass via the surface of the glass. In the case of strongly colored glasses, the absorption is so high just in the region of the surface of the glass that only relatively thin glass layers are heated through. In such cases, additional electrical heating is often provided by electrodes which are introduced through the base of the tank.

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In the case of the electrically heated tanks, the glass melt is heated conductively using alternating current by electrodes, i.e. the glass melt is heated directly. The electrodes are introduced into the glass melt either through the tank base or through the side walls of the tank and are surrounded by the glass melt on all sides.

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The electrode material used is often molybdenum or platinum. The Mo electrodes have a very strong tendency to be oxidized, and therefore should not generally come into contact with  
5 air. Glass melts containing redox elements, such as for example  $\text{Sb}_2\text{O}_5$  and  $\text{As}_2\text{O}_5$ , can also attack the Mo or Pt electrodes.

Pt electrodes are significantly more resistant to oxidation  
10 but can only be used stably for a long time up to temperatures of 1 500°C, or for a short time up to 1 650°C.

Patents GB 644,463 and DE 100 05 821 have disclosed rod electrodes cooled by water alone. However, on account of the  
15 maximum current which can be applied per unit area of the electrodes, only a limited amount of power can be supplied using cooled rod electrodes. Heating of a melting unit with strongly cooled walls is only possible to a very restricted extent using an electrode of this type, since it is  
20 impossible to introduce higher power densities.

Electrodes with larger surfaces - known as plate electrodes - are described, inter alia, in patents SU 1016259 or DE 2705618. Electrodes of this type have the advantage that  
25 they can be exposed to higher current loads on account of the large electrode surface area. However, these plate electrodes are not cooled, and consequently in this case too the maximum melting temperature which can be reached is restricted to the application limit temperature of the electrode material.  
30 Although in SU 1016259 the walls of the melting unit are made cooler than the temperature in the center of the melting unit by virtue of the positioning of the electrodes in the interior of the melting unit, the electrodes are at the same temperature as the melt and are therefore the limiting factor  
35 for the maximum temperature which can be reached in the melt.

A similar approach is described in patents US 5961686 and US 6044667, in which only the inner region of the melting unit is heated using cooled top electrodes. The walls are additionally water-cooled. This arrangement allows the wall temperature to be kept at temperatures below 1 482°C, in order to avoid extensive corrosion. However, the maximum melting temperature is limited to 1 788°C by the electrodes being positioned in the hottest zone. The structure of the unit has the crucial drawback that only a small part of the total melting volume can be used for melting at the high temperatures. Furthermore, the unit is not suitable for refining, on account of the surface being covered by batch.

To allow the melting of glasses, glass-ceramics, ceramics or crystals at over 1 700°C, on the one hand the walls of the melting units and the electrodes located in the melt have to be cooled, and on the other hand more energy has to be supplied to the melt than is withdrawn from the melt through the cooled walls and electrodes.

The patent literature describes melting using radiofrequency in skull crucibles for the melting of high-melting glasses or crystals. For example, DE 199 39 779 describes the continuous melting of high-melting glasses using a radiofrequency-heated skull crucible.

In this context, the term skull crucible is to be understood as meaning a vessel whereof the walls comprise water-cooled metal tubes arranged close together. The sealing of the crucible is ensured by the melt freezing in the immediate vicinity of the tubes. This makes it possible to dispense with the need for refractory material.

The skull crucible is surrounded by a radiofrequency coil. Between the metallic tubes there has to be space, so that the radiofrequency can be introduced into the melt. The glass melt is heated directly with the aid of the radiofrequency.

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The advantages of melting using radiofrequency in a skull crucible consists in the fact that glass melts can be heated even to temperatures of over 1 700°C.

- 10 The direct introduction of the radiofrequency into the melt allows the melt to be cooler in the edge region of the melting unit than in the center. The cooled metal tubes cause a skull layer of material of the same type as the melt to form, and this skull layer can be constantly renewed.
- 15 Consequently, even high-melting or very aggressive glasses can be melted down and refined successfully.

- A further advantage of melting using radiofrequency consists in the fact that other refining agents, known as high-temperature refining agents, can also be used for refining at high temperatures. This makes it possible for example, as described in DE 19939771, to dispense with the use of toxic refining agents, such as arsenic oxide or antimony oxide.
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- 25 However, melting using radiofrequency has the drawback that the glasses, glass-ceramics, ceramics or crystals to be melted have to have a sufficiently high electrical conductivity at the melting temperature. The electrical conductivity of the melt must be high enough for the energy introduced by the radiofrequency to be greater than the thermal energy dissipated via the walls and in particular via the skull walls. Although the limit on the electrical conductivity required also depends on a range of apparatus parameters, in practice it has been found that the electrical
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- 35 conductivity of the melt should be above  $10^{-1} \Omega^{-1} \text{ cm}^{-1}$ .

The electrical conductivity of glasses and glass-ceramics is generally determined to a very significant extent by the alkali metal content and only to a lesser extent by the alkaline-earth metal contents of these glasses.

In practice, however, it has emerged that in particular the high-melting glasses, for which radiofrequency melting in the skull crucible would be particular suitable on account of the high temperatures, in most cases in fact have an electrical conductivity of below  $10^{-1} \Omega^{-1} \text{ cm}^{-1}$ , which is too low. Therefore, a range of important technical glasses cannot be processed using the radiofrequency melting technique.

These glasses include, for example, the glasses with a high thermal stability and a high resistance to temperature changes, which are required, for example, for pharmaceutical packaging applications, lamps that can be exposed to high temperatures and fireproof glasses. Glasses of this type have to have both a high transformation temperature and a low linear thermal expansion, these glasses generally having a high melting temperature and a low electrical conductivity.

A further group of glasses, such as for example display glasses, have to be coated during further processing. In this case, it is undesirable for the glasses to contain alkali metals, such alkali metals can easily diffuse out of the glasses and in this way, for example, enter the functional layers of the display. On account of the low or absence of alkali metal content, these glasses likewise have an electrical conductivity which is too low to be, for example, sufficiently coupled to radiofrequency.

Accordingly, there is a demand for a method and an apparatus which make it possible to melt glasses, glass-ceramics,

ceramics and crystals even at high temperatures, for example above 1 600°C, preferably above 1 700°C, while the glasses, glass-ceramics, ceramics and crystals may also have an electrical conductivity lower than  $10^{-1} \Omega^{-1} \text{ cm}^{-1}$ .

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With the method and apparatus, on the one hand it should be possible to sufficiently cool the walls of the melting unit to prevent the melt from chemically attacking the walls, and on the other hand to supply the melt with more energy than is removed from it through the cooled walls.

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According to the invention, this object is achieved by a method having the features of claim 1 and an apparatus having the features of claim 30.

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Accordingly, the invention provides a method for heating a melt in a melting vessel with cooled walls, the melt being conductively heated, and the current flowing between at least two cooled electrodes, wherein the electrodes each replace part of the wall of the melting vessel. In the context of the invention, this is also to be understood as meaning that during introduction or insertion of electrodes into a melting vessel of predetermined geometry, the sum of the surface areas of melting vessel and electrodes in the region of the melt remains constant. For example, if a defined geometry of the melting vessel is selected, the electrodes take up part of the walls of the melting vessel, with the selected geometry being retained. By contrast, hitherto the wall surface area has been increased, for example by the additional introduction of finger electrodes, so that the cooling power also increases accordingly.

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For this purpose, the electrodes may advantageously be inserted into cutouts in the cooled walls of the melting vessel. The arrangement according to the invention creates a

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favorable ratio of the surface proportion of the melting vessel through which energy is introduced into the melt to the surface fraction formed by cooled walls. This also makes it possible, by suitably setting or controlling the cooling power, to heat at least a region of the melt by the current to a temperature which may be significantly above the temperature of the surface of the melt-contact material. In particular, in the melt it is possible to reach a temperature which is above the application limit temperature, such as in particular above the melting or decomposition temperature of the melt-contact material of at least one of the electrodes or of the wall material. The decomposition is to be understood in this context in particular as meaning chemical decomposition, such as corrosive attack, sublimation or evaporation.

Application limit temperatures for different melt-contact materials are known, inter alia, from the publications

- 20 [1] Johnson Matthey Noble Metals: "Platinum Sheet Material for the Glass Industry",
- [2] Glass Science and Technology 13: "Metals in Glassmaking", Roland Kirsch (Ed.), Elsevier, Amsterdam, London, New York, Tokyo, 1993,
- 25 [3] E. Drost, H. Gölitzer, M. Poniatowski, S. Zeuner: "Platinwerkstoffe für Hochtemperatur-Einsatz" [Platinum materials for high-temperature use], Metall - Internationale Zeitschrift für Technik und Wirtschaft No. 7/8 1996, pages 492 - 498, Metallverlag
- 30 Berlin/Heidelberg 7/8 1996, and
- [4] "Precious Metals Science and Technology": L.S. Benner, T. Suzuki, K. Meguro, S. Tanaka (Eds.), The International Precious Metals Institute, USA, 1991,

the content of disclosure of which in this respect is hereby incorporated in the subject matter of the present invention.

In this context, the application limit temperature of melt-contact materials is determined, inter alia, by the chemical composition, the grain growth, the resistance to oxidation, the resistance to corrosion in the melt, the hot strength, the creep rupture strength, the creep rate, the duration of use and the type of heating. For pure platinum, despite the good chemical stability, a maximum long-term application temperature of 1 400°C is stipulated on account of the low hot strength (cf. in this respect, by way of example, publication [1]). In many cases, as is known, inter alia, from publications [2] and [4], platinum can also reliably be used up to 1 500°C.

In order, for example, to achieve particularly rapid and effective refining of the melting material, it is expedient if the temperature of the melt is kept at least in a range above 1 600°C, preferably above 1 700°C.

By virtue of the electrodes being arranged in the melting vessel in accordance with the invention, it is also possible to use a material such as platinum as melt-contact material, which otherwise could not generally be used for a prolonged period for temperatures above 1 600°C on account of the ability of this material to withstand thermal loads.

The temperature of the melt-contact surface of the electrodes, in particular of electrodes comprising platinum as melt-contact material, is preferably restricted to at most 1 500°C. This prevents electrode material which influences the properties of the melt material, such as for example the color, from migrating into the melt in relatively large quantities. Moreover, this considerably lengthens the service



life of the electrode.

Adding other platinum group metals to Pt, such as for example Rh, Ir, or Ru, to the alloy in individual cases also allows  
5 even higher hot strengths to be achieved, as disclosed, for example, in publications [1], [2] or [3]. However, crystal growth generally commences at temperatures higher than 60% of the melting temperature  $T_s$ , which leads to a reduction in the hot strength and therefore limits the application limit  
10 temperature for PtRh10 to 1 550°C, for PtRh20 to 1 650°C and for PtRh40 to at most 1 700°C. Moreover, PtRh alloys are generally ruled out if it is unacceptable for the glass to be colored by rhodium.

15 The use of fine-grain-stabilized platinum or platinum alloys of this type, such as for example PtRh10, allows application limit temperatures of 1 500°C or 1 650°C, since the coarse grain formation in this case only begins at temperatures of use higher than 85% of the melting temperature  $T_s$  (cf. in  
20 this respect also publications [1], [2] and [3]). Fine-grain-stabilized materials, such as the fine-grain-stabilized platinum mentioned above, are also known as dispersion-strengthened materials or oxide-dispersion-hardened materials.

25 Moreover, the application limit temperature may be limited by the chemical stability of the melt-contact materials, which depends, inter alia, on the presence of polyvalent elements in the melt. These often form low-melting alloys with the  
30 melt-contact materials, which can considerably reduce the application limit temperature. If there are no intended additions of polyvalent elements, for example in the form of refining agents, impurities are generally still present in the glasses.

In the case of ceramic materials, application limit temperatures may result inter alia from chemical decomposition in contact with a glass melt. For example, fused-cast ceramic materials, such as high zirconium-containing ceramic material (HZFC) or AZS (aluminum-zirconia silica) can generally only be used as melt-contact material up to at most 1 650°C.

The application limit temperature may also be reduced through oxidation. In particular when using iridium, the sulfur content in the glass also has to be taken into account, since the formation of  $\text{IrS}_2$  may considerably restrict the use of Ir.

Mo can usually be used in glass melts at up to 1 700°C. With Mo, however, spontaneous grain growth commences between 1 600°C and 1 800°C, which is associated with a considerable drop in the strength, so that this may produce an application limit temperature within this temperature range. A similar statement applies to W. In this case, total recrystallization has concluded at just 1 500°C. The application limit temperature for Mo and W is, however, determined to a lesser extent by the mechanical properties at high temperatures than by the chemical stability. Mo and W oxidize in air or oxygen at 400°C. It is also known from publication [2] that polyvalent compounds dissolved in the glass likewise lead to the formation of  $\text{MoO}_3$  and/or  $\text{WO}_3$ . Mo reacts with  $\text{SiO}_2$  at 1 650°C and with  $\text{Al}_2\text{O}_3$  at 1 700°C, to form  $\text{MoO}_3$ . As a result, above these temperatures undesirable dissolution and migration of molybdenum into the melt may occur, and consequently application limits are likewise reached at these temperatures.

If  $\text{Sb}_2\text{O}_3$  is present in the glass as a refining agent,  $\text{Mo}_3\text{Sb}_7$  may be formed beyond  $600^\circ\text{C}$  to  $900^\circ\text{C}$ , and the application limit temperature of Mo may be reduced considerably on account of the formation of a liquid phase and associated  
5 destruction of the component.  $\text{As}_2\text{O}_3$  likewise reacts with Mo to form low-melting eutectics. An important factor in the application limit temperature of Mo and W is presented by molybdates and tungstates, which may be formed in melts containing alkali metals. These compounds have lower melting  
10 points than the pure oxides. Therefore, the application limit temperatures may also depend on the alkali metal content of the respective glasses.

The invention provides an apparatus and a method in which the  
15 current density on the surface of the melt-contact material can be kept at a particularly low level, so that there is little heating of the melt-contact material. In the electrode according to the invention, the total surface area, made up of the electrode surface area and vessel surface area, is not  
20 increased compared to conventional electrodes, since the electrode takes up part of the vessel surface area. However, the proportion of the surface area of the melting vessel which introduces energy into the melt does increase. By contrast, with conventional electrodes, in order not to  
25 exceed the maximum possible current density, the electrode surface area had to be increased, which resulted in a larger total surface area, made up of the electrode and vessel surface areas, which in turn leads to an increased removal of heat.

30 An apparatus according to the invention for the heating of melts, in particular for the high-temperature refining of melts, by contrast, accordingly comprises  
- a melting vessel with cooled walls for receiving melting  
35 material, and

- at least two electrodes for the conductive heating of the melt, which in each case replace part of the walls of the melting vessel. By way of example, these electrodes can be inserted into cutouts in the wall of the melting vessel.

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The arrangement according to the invention of the electrodes and the direct conductive heating of the melting material makes it possible to set a temperature gradient in which at least a region of the melt can be kept at a temperature which is significantly higher than the temperature of the surface of the melt-contact material, even, for example, higher than the application limit temperature of the melt-contact material of the electrodes. It is in this way possible in particular to accelerate refining operations. For this purpose, the electrode surface area advantageously takes up more than 5%, preferably more than 10%, and particularly preferably more than 15%, of the wall surface of the melting vessel. Such large-area electrodes keep the current density and therefore the heating of the electrodes to a low level. Furthermore, a homogeneous introduction of power over the entire melt volume, without any dead volumes, is achieved.

The inventors have discovered that it is possible to set a temperature gradient even in melts with an electrical conductivity of lower than  $10^{-1} \Omega^{-1}\text{cm}^{-1}$ . One advantage of the method compared, for example, to inductive radiofrequency heating therefore resides, inter alia, in the fact that high-temperature refining, in particular with at least regions of the melt at temperatures over 1 600°C, preferably over 1 700°C, can be carried out even in the case of melts with an electrical conductivity of lower than  $10^{-1} \Omega^{-1}\text{cm}^{-1}$ . An advantageous high-temperature refining process is described, inter alia, in DE 199 39 771, the content of disclosure of which in this respect is hereby also incorporated in the

subject matter of the present invention.

The required conductivity of the melt is subject to scarcely any restrictions with regard to the feasibility of the method according to the invention, since the operating voltage of the electrodes can be adapted accordingly. At the melting temperature, the electrical conductivity of the melt is preferably in a range from  $10^{-3}$  to  $10^2 \Omega^{-1}\text{cm}^{-1}$ , particularly preferably in a range from  $10^{-2}$  to  $10^1 \Omega^{-1}\text{cm}^{-1}$ .

The electrodes used for the apparatus according to the invention for the heating of melts, in particular for the high-temperature refining of melts, may particularly advantageously also be heating apparatuses as described in the PCT application, filed on the same date as the present invention, in the name of the Applicant entitled "Heating apparatus with electrode for the conductive heating of melts", the content of disclosure of which with regard to the electrodes of the apparatus described here is hereby also incorporated in its entirety in the subject matter of the present application.

The structure of the electrodes can be divided into three groups: each of the groups has to perform different roles.

The first group comprises the melt-contact material and the electrical supply conductors.

The role of the melt-contact material is to feed the electrical energy into the melt. One surface of the material is in direct contact with the melt, and therefore the material has to be as inert as possible with respect to the melt. Current can be supplied from the outside via suitable terminal lugs.

The second group comprises the cooling. The role of the cooling is in particular to set defined temperature profiles in the materials of the electrode structure. The temperature profiles are selected in such a manner that overheating and excessive corrosion of the materials is ruled out. To enable the temperature to be set, the electrode advantageously comprises at least one controllable cooling circuit.

A preferred structure of the electrode consists in the electrode being equipped with a double cooling system for two different cooling media. The device for cooling the electrodes may therefore advantageously comprise at least two cooling circuits, which in particular can be set or controlled independently of one another. The cooling circuits may advantageously be designed for two different cooling media; in particular air, aerosols and water are suitable cooling media. A further role of the cooling, moreover, is to prevent medium from running out between cooled walls and cooled electrodes.

The third group comprises the supporting structure. The supporting structure serves to realize the electrical supply conductors, the melt-contact material and the cooling in a structure suitable for the electrode function. This primarily involves ensuring the exchange of thermal energy between the cooling and the melt-contact material. Suitable materials for the thermal and mechanical stability have to be used. Ceramic materials, inter alia, are suitable for this purpose.

The supporting structure may comprise one or a plurality of different layers or parts, in order to ensure the exchange of thermal energy. A suitable melt-contact material in particular for glass melts is, for example, a material which comprises electrically conductive ceramic, such as for

example  $\text{SnO}_2$  ceramic and/or refractory metals, such as in particular platinum metals, for example iridium, rhodium, platinum and their alloys or high-melting refractory metals, such as tungsten, molybdenum, tantalum, osmium, hafnium and their alloys. Moreover, the melt-contact material may comprise a fine-grain-stabilized material. These are generally distinguished by a high strength and a good long-term stability. Fine-grain-stabilized materials of this type may, for example, comprise high-strength platinum or iridium materials.

At least one of the electrodes may advantageously also include at least two electrode segments. The electrode segments or electrode units are in this case preferably well electrically insulated from one another, and the electrode units or segments are preferably arranged at such a short distance from one another that the melt cannot flow through the spaces between the electrodes.

Cooling the preferably large-area electrodes combined, at the same time, with conductive heating can create in the melt a temperature distribution whereby large regions of the melt are significantly hotter than the melt-contact surface of the electrodes. Even with active cooling of the electrodes, the electrode arrangement and configuration according to the invention allows more energy to be introduced into the melt than is dissipated by the cooled electrodes and the further walls.

Accordingly, the apparatus according to the invention may advantageously also comprise a device for cooling the electrodes, in particular for cooling the melt-contact material of the electrodes, in order, for example, to prevent the melt-contact material from overheating.

In this context, it is also particularly advantageous if the cooling is controlled, so that the electrodes are prevented from overheating and the cooling power can be optimized for minimum dissipation of heat.

The cooling is preferably effected by passing a cooling fluid, such as in particular air and/or water, through the electrodes. For this purpose, the apparatus according to the invention may advantageously accordingly comprise a fluid-conveying device. In this case, the cooling is particularly effected by passing through a gaseous cooling fluid, such as for example air, by means of a low-pressure blower. The coolant is advantageously passed through the electrodes at a pressure difference of less than 1 000 mbar preferably than 500 mbar, particularly preferably less than 150 mbar. The passages for routing the cooling fluid in the electrodes are for this purpose dimensioned such that a sufficient flow of coolant is achieved even at such a low pressure difference built up by the low-pressure blower.

To allow a defined temperature gradient to be produced from the hottest region of the melt to the melt-contact material of the electrodes, the apparatus according to the invention preferably also comprises a device for controlling the cooling power of the electrodes. The electrodes integrated in the wall of the melting vessel and the device for controlling the cooling power are preferably designed in such a way that the temperature of the melt-contact surface of the electrodes can be controlled very accurately within a wide temperature range by means of the installed cooling system.

The temperature of the electrodes is controlled in such a way that during the melting operation the temperature of the electrodes is always below the temperature at which the



electrode material is chemically attacked to a disruptive extent by the melt.

In the case of platinum being used as electrode material, for example, the temperature of 1 550°C should not be exceeded.

If there is a high level of convection in the melt, the temperature of the electrodes may under certain circumstances have to be reduced further, so that in this case too the electrodes are not attacked to a disruptive extent by the melt.

A significant factor in the heating of the electrode surface and the dissipation of heating power is also the absorption of infrared radiation from the melt. Whereas an increase in the temperature of the melt compared to the walls of the melting vessel can be achieved by cooling, on the other hand it can also be achieved by virtue of the melting vessel having a surface which reflects infrared. The infrared-reflecting surface reduces the heating of the walls. Accordingly, an infrared-reflecting surface is equivalent in terms of its effect to cooling of the walls within certain limits. Accordingly, the invention also provides an apparatus for heating melts which comprises a melting, conditioning and/or refining vessel for receiving melting material. In this case, the melting vessel has a surface which reflects infrared at least in regions. An apparatus of this type may likewise be provided with electrodes for conductive heating. However, it is also possible for other heating methods, for example radiofrequency heating, to be used. To achieve good reflection properties, the infrared-reflecting surface may be polished. It may also be provided with an infrared-reflecting coating, in which context in particular a gold, platinum, nickel, chromium or rhodium coating is suitable. By way of example, gold-coated walls have already reduced the heating

power required by up to 20%.

If an apparatus of this type is designed for conductive heating, the infrared-reflecting surface may in particular  
5 comprise the surface of the melt-contact material of at least two electrodes for the conductive heating of the melt which replace part of the walls. In this case, a significant effect is achieved even if only the surface of the melt-contact material is designed to reflect infrared.

10 The method according to the invention also has the advantage over melting units which are operated with radiofrequency and in which the melting material is completely surrounded by water-cooled skull walls in skull crucibles, that the  
15 preferably cooled electrodes installed in the melt extract significantly less heat from the melt.

Furthermore, the electrical converters for frequencies in a range from 50 Hz to 50 kHz have a considerably better  
20 efficiency than the converters for radiofrequency which are customarily used in skull crucibles, allowing operating costs to be significantly reduced.

Moreover, it is advantageous if the wall of the melting  
25 vessel is also cooled, at least in a region, in order on the one hand to protect the walls from overheating and on the other hand to cause a temperature gradient within the melt. The apparatus according to the invention, as is the case, for example, with skull crucibles, therefore preferably comprises  
30 a device for cooling at least a region of the wall of the melting vessel.

It is advantageous in particular if the preferably large-area electrodes are arranged in electrically insulated fashion, so  
35 that the current for the conductive heating can flow only

through the glass melt and not across the walls.

Depending on the arrangement of the electrodes and the geometry of the melting vessel, the electrodes may  
5 advantageously comprise plate and/or button and/or rod electrodes. Since the electrodes are exposed to a certain amount of wear even when operating below the temperature range at which decomposition of the electrode commences, it is furthermore advantageous if the electrodes are secured  
10 exchangeably to the apparatus.

The electrodes are preferably operated with an alternating current of 50 Hz to 50 kHz, particularly preferably from 2 kHz to 10 kHz. The alternating current substantially  
15 prevents corrosion to the electrodes, since corrosion decreases with increasing frequency of the current. Accordingly, an apparatus according to the invention may also advantageously comprise a device for generating alternating current, such as for example a medium-frequency transformer  
20 or an alternating current generator, the alternating current preferably having a frequency within one of the ranges mentioned above.

Tests have shown that in the case of melts with a poor  
25 electrical conductivity, the introduction of energy via large-area cooled electrodes which are not integrated in the walls is insufficient to heat these melts if the cooled electrodes are located in a melting unit whereof the walls are likewise cooled. The removal of energy from the melt via  
30 the cooled walls and the additional removal of energy via the cooled electrodes is then higher than the introduction of energy into the melt in the case of melts with a low electrical conductivity. In this case, it is also not sufficient to make the melt-contact surfaces of the  
35 electrodes larger, since this not only increases the

introduction of energy, but also causes additional heat to be dissipated via the larger electrode. On the contrary, there is a risk that in apparatuses known from the prior art a melt which is already hot will be cooled to such an extent by the  
5 dissipation of heat that it will be disconnected on account of the falling temperature and the associated falling electrical conductivity.

On account of the fact that, by contrast, the cooled,  
10 preferably large-area electrodes according to the invention are integrated in the cooled walls in such a way that they themselves form part of the walls, the cooling total surface area of the unit is not increased, and consequently even in the case of melts of a poor electrical conductivity the  
15 introduction of energy can be kept at a higher level than the removal of energy.

For the method for heating the melt, it is advantageous if the temperature of the walls of the melting vessel and the  
20 electrodes are kept below the temperature at which the materials of the walls and of the electrodes are chemically attacked to a significant degree by melt. In order, therefore, to ensure a long service life of the melting unit at high melting temperatures, the cooled walls, in particular  
25 made from refractory material, have to be cooled by cooling systems to such an extent that the chemical attack of the melt on the refractory material is negligible.

At high melting temperatures, the convection of the melt also  
30 increases, and therefore so does the chemical attack on the refractory material. In this case, the temperature of the walls should be reduced further, in order to avoid increased corrosion of the walls as a result of the strong convection. However, it is generally advantageous if the electrodes  
35 and/or walls of the melting vessel, for example when using

refractory ceramic as electrode or wall material, are substantially chemically resistant to the melt, so that the walls do not have to be cooled too far and the removal of energy through the walls does not become too great. Moreover, it is advantageous if the material of the electrodes and walls has a good thermal conductivity, to allow the walls to be effectively cooled.

The cooled walls used may preferably also be skull walls. The skull walls have the advantage that a skull layer of the same type of material as the melt is formed on the cooled metallic tubes and is constantly reformed at high temperatures. The skull walls have also proven suitable for melts which are chemically highly aggressive with respect to ceramic refractory materials.

Despite the thin thermally insulating skull layer, skull walls still extract very large amounts of heat from the melt. Therefore, inter alia refractory ceramics may advantageously also be used as material for the walls of the melting vessel, in which case it is preferable also for the walls made from refractory ceramic to be cooled.

It has proven advantageous, at least during the start-up process, for the skull walls, which preferably comprise cooled metallic tubes, such as for example copper tubes or steel tubes, to be lined with a material with a poor electrical and thermal conductivity, preferably in the form of ceramic plates or slip, in particular  $\text{SiO}_2$  slip, on the side facing the melt. This allows the dissipation of heat to be reduced until the supply of electrical energy has reached a sufficiently high level at relatively high melting temperatures.

It has likewise proven advantageous for the cooled tubes of the skull walls to be such that they do not release any coloring ions into the melt through the skull layer. This can be achieved on the one hand by the metal tubes either  
5 consisting of platinum or being coated with platinum. Metal tubes made from aluminum can easily be oxidized at the surface but do not release any coloring ions into the surface.

10 Furthermore, it is also possible for the metal tubes to be coated with plastic, as is described, for example, in DE 100 02 019. Plastic coatings can be very chemically resistant and do not generally release any metal ions to the melt which can cause undesirable discoloration in the fully  
15 melted and processed product.

Moreover, particularly when using skull walls, it is important for there to be no conductive connection between the electrodes used and the electrically conductive skull  
20 tubes, since otherwise heating of the melt is not possible on account of the resistance distribution in the system. Therefore, suitable resistance bridges have to be inserted in the skull and toward the electrodes, so that the current for conductive heating does not flow across the skull, but rather  
25 substantially through the melt.

As well as the frequency of the current, the current density at the interface with the melt also has a strong influence on the electrolysis and therefore on the corrosion of the  
30 electrodes. Tests have shown that it is advantageous to use electrodes with as large an area as possible and/or to create the largest possible melt-contact surface, in order to keep the current density as low as possible. To prevent damage to the electrodes or the introduction of electrode material into  
35 the melt, it is advantageous if the electrodes are

dimensioned in such a way that a current density of 5 A/cm<sup>2</sup> is not exceeded for a given heating power.

Moreover, tests have shown that at high melting temperatures, in particular at melting temperatures over 1 700°C, a significant part of the energy in the melt is transported through convection. Since the density of the glass decreases with the temperature, the hottest zone is usually located in the upper part of the melting unit.

As the temperature rises, the electrical conductivity of a melt increases exponentially. Therefore, the electrical conductivity is highest in the upper part of the melting unit, where the current density on the electrodes is particularly high. In this context, it has been found that it is possible to prevent overloading of the electrodes if the electrodes are arranged in the lower part of the melting unit. Furthermore, arranging the electrodes in the lower part of the melting unit has the advantage that sufficient convection is present even in the lower part of the melting unit, and therefore flow dead zones are avoided or reduced. Therefore, even the top edge of the electrodes is always below the melt bath surface, which avoids an air-melt-electrode three-phase boundary, which is particularly critical in terms of corrosion. In this context, it has proven advantageous in particular for the electrodes in the lower part of the melting vessel to be arranged below the melt bath surface in the region of the lower two thirds of the height of the melting vessel.

Overloading of the electrodes can also be avoided if the melt-contact surfaces of the electrodes are arranged obliquely with respect to one another, in which case the melt-contact surfaces tend to diverge toward the melt bath surface, so that the resistance path between the electrodes

is longer in the upper part near the melt bath surface than in the lower part. This makes it possible, for example, for the higher conductivity to achieve a homogeneous current density in the vicinity of the melt bath surface, caused by the higher temperature in the upper region of the melt, to be at least partially compensated for. By way of example, for this purpose the melting vessel may be of a form which widens upward in frustopyramidal or frustoconical form. As a further measure for reducing the maximum current loading on the electrodes, it is also possible, for example, for the upper edge thereof to be rounded.

In the case of relatively large installations, the heating may also be effected by more than one electrode pair. Therefore, one embodiment of the apparatus provides a plurality of electrode pairs and/or a plurality of pairs of electrode segments. These may in particular be operated with a plurality of heating circuits that can be controlled independently. For example, two circuits can be operated in the form of a Scott circuit.

In the present context, the term an electrode pair is to be understood in the electrical sense as a pole pair. In this context, it is also quite possible to combine a plurality of electrodes and/or a plurality of electrode segments on one electrical pole, and/or one electrical terminal. It is also possible for a plurality of electrode pairs to be arranged above one another at the side walls of the melting vessel. The vertical temperature stratification can be deliberately set in this way. Suitable electronic actuation also allows heating circuits that can advantageously be controlled independently and each of which are assigned an electrode pair to be operated successively at offset times.



To avoid excessively high voltages in combination with a low electrical conductivity of the melt, it is also possible for the electrode surface to be increased by working with one or more bottom electrodes and one or more electrodes in the side walls. The electrode pairs may also be supplied by a plurality of current sources.

A plurality of electrode pairs arranged vertically or horizontally next to one another can also be arranged so as to allow targeted influencing of the spatial temperature distribution. By way of example, the vertical temperature stratification can be set in such a way by two electrode pairs and heating circuits operated independently that flow dead zones are avoided in the lower part of the melting unit.

Furthermore, the electrodes may advantageously be arranged and connected in such a way that the majority of the electrical power drops predominantly in the lower region of the melting unit.

The melting vessel may advantageously have a square or rectangular basic contour, so that the electrodes can have planar melt-contact surfaces. However, to reduce the specific surface area of the melt for the same volume, the melt vessel may also be of cylindrical design with a circular or oval basic contour. In this case, the electrodes may also be configured, inter alia, in ring form and, for example, take up a segment of the height of the wall of the melting vessel. The apparatus may also have one or more electrodes arranged at the base of the melting vessel. An electrode for a melting vessel shaped in this way may also, for example, form a ring segment of the wall of the melting vessel. Bottom electrodes may advantageously also be arranged in such a way that there is the possibility of the inlet or outlet for melting material to be at the base.

The melting vessel may also have a polygonal basic contour which, for example, closely approximates to a round or oval basic contour and can be produced in a simple way from planar wall segments.

The melting unit according to the invention with the cooled walls and the large-area electrodes integrated therein can be used both to melt down and to refine glasses, glass-ceramics, ceramics or crystals.

It is also possible for two of these units, for example one for melting-down and another for refining, to be connected in series. Furthermore, the units can be used for both discontinuous and continuous melting.

If the unit is used for melting down, the melting-down operation can be accelerated by bubbling with a gas, for example with oxygen or noble gas. For this purpose, the apparatus may advantageously have at least one blowing nozzle or bubbling nozzle, preferably arranged at the base of the melting vessel.

If the walls of the melting unit comprise skull walls and cooled electrodes, the upper part of the melting unit, to protect the metal tubes of the skull, may be configured in the form of a mushroom at the melt bath surface, as described, for example, in DE 199 39 772.

For discontinuous melting and for complete emptying of the melting vessel, for example in order to carry out maintenance work, it is advantageously possible for at least one outlet nozzle to be fitted in the base of the melting unit.

Moreover, the apparatus may advantageously have a cooled bridge, which is preferably arranged in such a way that it is immersed in the melt from above through the melt bath surface. This makes it possible both to melt down the batch continuously and refine the melt continuously in just one melting unit. In this case, the melting unit can be divided into a melt-down part and a refining part by a bridge formed from water-cooled metal tubes.

As is also the case when melting using radiofrequency, in the method according to the invention the melt first of all has to be heated to a temperature at which the electrical conduction of the melt is high enough for the melt to be sufficiently well connected, for conductive heating, for the energy which is introduced to be higher than the energy which is dissipated via the cooled walls and electrodes.

When melting using radiofrequency, it is most cases sufficient for a small part in the interior of the melt to have a sufficient electrical conductivity and to be well connected. The radiofrequency energy is concentrated in this region and heats it further, with the result that this region propagates continuously until it fills the whole of the melting unit.

The melting method according to the invention is based on conductive heating of the melt, which means that electrical conduction across the melt has to be produced between the electrodes. It is therefore not sufficient for a melting region in which the electrical conduction is high enough to be present in the interior of the melt. Rather, the resistance of the melt between the electrodes has to be sufficiently lowered at least in a region, or the electrical conductivity of the melt has to be increased sufficiently far at least within a region, for the applied voltage or the

current density to be sufficient to heat the melt to a greater extent than the heat loss through the walls. For this purpose, the apparatus according to the invention may moreover advantageously have a device for additional heating.

5 The device for additional heating may in this case expediently comprise, for example, at least one fossil burner and/or at least one plasma torch and/or at least one resistance heating element and/or at least one infrared radiator.

10

By way of example, if the additional heating is fitted above the crucible, to start up the conductive heating process first of all a melt path with sufficient electrical conductivity has to be heated for a sufficient extent for the  
15 conductivity to be high enough for a sufficiently high current to flow. In this case, for example when using large crucibles, correspondingly high-power additional heaters can be installed.

20 Even when using additional heating, the dissipation of heat via the electrodes, even without active cooling of the electrodes, can cause the melt-contact surface of the electrodes to remain at a lower temperature than inner regions of the melt or of the melting material, and  
25 consequently this effect impedes the flow of current, in particular in the vicinity of the electrode surface. It is therefore advantageous if at least one of the electrodes also comprises a heating apparatus, by which the melting material at the electrode surface and/or the melt-contact surface can  
30 be heated directly. This allows the electrode to be heated automatically at least from time to time until, for example, the heating power provided by conductive heating of the melt is sufficiently high.

Moreover, when restarting the apparatus, the problem often arises whereby an insulating air gap is present between melt-contact material and cooled melting material. This air gap is formed through shrinkage of the melting material during cooling. If a voltage is applied to the electrode when the air gap is present, the air gap can be locally bridged by ionization and the current can shoot through at this location, which can lead to damage to the melt-contact material. With direct heating of the electrodes, the melting material can be initially melted in the region of the melt-contact material, and in this way comes back into electrical contact with the electrode by forming a large-area conductive bridge.

A particularly suitable heating apparatus is an ohmic heating device. This device may preferably comprise a current source which is connected to the melt-contact material or a conductive material beneath it, thereby forcing a current through the melt-contact material or the conductive material beneath it.

However, as an alternative or in addition, the heating apparatus may also comprise an apparatus for heating a cooling fluid. In this way, the electrode can be both heated and cooled using the same fluid. Accordingly, the heating device also does not have to be arranged directly beneath the melt-contact surface, but rather can be arranged at virtually any desired suitable point in the cooling fluid circuit. The heating apparatus may, for example, comprise an electrical and/or fossil heater and/or a waste heat heater.

Preheating by heating the coolant in particular by means of electrical energy, waste heat or preferably using fossil energy carriers is also advantageous, for example, in order to prevent the precipitation of moisture on the electrodes by

virtue of it being heated above the dew point of the furnace upper atmosphere of the melting apparatus. Moisture may be formed in the melting apparatus, for example, in relatively large quantities during initial operation of the unit when  
5 the melting material is being preheated using fossil burners.

There are a range of methods for heating the melt to a sufficient extent for it to reach a temperature at which the electrical conduction of the melt is sufficient to allow  
10 further heating with the aid of the electrodes or connection of the melt.

For example, for initial operation of the melting unit, the method according to the invention may advantageously comprise  
15 a starting operation in which solid melting material located in the melting vessel is melted down or introduced into the melting vessel in molten form. The following text is to describe, by way of example, this type of melt start-up. However, the invention is not restricted to this specific  
20 start-up method.

To start up the melting unit according to the invention, by way of example, charge cullet or batch is placed into the melting unit and partially melted by means of one or more  
25 fossil burners, plasma torches or infrared heating in the upper furnace until the electrical conduction is sufficient to start the direct electrical heating. The technical limit in this context is the maximum voltage which can be provided by a device for generating alternating current, such as for  
30 example a medium-frequency transformer. To allow current to flow at a lower contact resistance, the electrodes, during the starting operation, can be resistance-heated or operated without or with only little cooling.

To facilitate the starting operation, the electrodes may also be arranged displaceably. In this case, the electrodes can be pushed together prior to the starting operation, so that the volume between the melt-contact surfaces is reduced. This smaller melt volume can then easily be heated to a temperature at which the melt has a conductivity sufficient for the conductive heating by the electrodes. During the starting operation, the electrodes can be pulled apart again to their operating positions, increasing the melting volume.

The electrodes and/or cooled walls, during the start-up process or the starting operation, can be heated by a heating apparatus to a sufficient extent for their temperature to be above the dew point of the furnace upper atmosphere. This prevents moisture from precipitating on the electrodes; such moisture, as a film of water, leads to short circuits during initial operation of the electrodes. It is particularly preferable for preheating of this type to comprise cooling-water preheating.

According to one embodiment of the invention, to melt down the melting material, starting electrodes are introduced into the melting vessel and a current is passed through the melting material via the starting electrodes. In this way, a melt can initially be produced in a small region of the melting unit. Moreover, the starting electrodes can be moved apart during the starting operation, so that the region comprising molten material increases in size. This region of molten material which increases in size during the starting operation can then ultimately come into contact with the actual electrodes or molten regions in the vicinity thereof, which have been melted, for example, by means of a heating apparatus for heating the electrodes. It is in this way possible to produce a melting path with a sufficient conductivity of the melting material between the electrodes,

so that the conductive heating of the melt can start operating. The electrical conductivity of the melt increases exponentially as the temperature of the melt rises, and a transformer can be used to switch to a lower voltage, since a  
5 strong current is required to introduce a high electrical power.

In parallel with the rise in the introduction of electrical power, it is possible to lower the power of the upper furnace  
10 heating accordingly as the electrical conductivity of the melt rises. Since the electrical conductivity of the melts, for example in the case of glass melts, rises very rapidly with the temperature, the electrodes can easily burn through. Therefore, the cooling of the electrodes and the heating  
15 power can be controlled accurately as a function of the temperature and the composition of the melt.

According to the invention, this can be achieved by the temperatures of the electrodes being accurately monitored and  
20 the temperature of the electrodes being accurately set with the aid of a control system and the cooling system fitted in the electrodes. On the one hand, the electrodes must not extract too much heat from the melt, while on the other hand they must not become sufficiently hot for them to corrode or  
25 even burn through. If the walls of the melting unit comprise skull walls, the skull walls can be covered with ceramic materials or with slip. The slip may, for example, consist of milled quartz material. Covering the skull walls in the start-up phase prevents an excessive loss of heat through the  
30 walls.

Furthermore, for initial operation of the melting unit or for the starting operation, it is possible to convert the melt from a melt with a high electrical conductivity to a melt  
35 with a low electrical conductivity.



It has been found that strong convection commences in the melting unit or the melting vessel if the temperature difference between the melt in the edge region of the melting vessel and the melt in the center region of the melting unit amounts to more than  $150^{\circ}\text{K}$ , preferably more than  $250^{\circ}\text{K}$ .

Strong convection is advantageous to recirculate the melting material, so that the entire melt, or at least the majority thereof, passes through the region which is at an elevated temperature compared to the electrode surface. When the melt-contact surface of the electrodes is at a temperature of  $1500^{\circ}\text{C}$ , the melting temperature in a region preferably arranged in the center of the melting vessel can accordingly be over  $1650^{\circ}\text{C}$ , preferably over  $1750^{\circ}\text{C}$ .

The possibility, according to the invention, of heating a melt to high temperatures even above loading limits for electrode and wall material brings with it a range of advantages. Firstly, even high-melting glasses, glass-ceramics, ceramics or crystals can be melted. A further advantage is that the chemical reactions and physical processes take place significantly more quickly at higher temperatures than at lower temperatures. For example, both the melt-down processes and the refining operations take place significantly more quickly at higher temperatures. Increasing the temperature by  $200^{\circ}\text{K}$  accelerates the chemical reactions and the physical processes by a factor of 3 or even higher. As a result, by way of example, included bubbles in the melting material can be removed more quickly. For example, the rate at which bubbles rise in a melt is given by:

$$v = \frac{2 \rho \cdot g \cdot r^2}{9 \eta(T)}$$

In the above,  $\rho$  denotes the density of the melting material,  $g$  denotes the gravitational acceleration,  $r$  denotes the bubble radius and  $\eta(T)$  denotes the temperature-dependent dynamic viscosity. If the temperature of the melt is increased, the thermal expansion causes the bubble radius to increase, the diffusion of gases out of the melt into the bubble to be accelerated and the viscosity of the melt to be reduced. To additionally accelerate the chemical and physical reactions, it is advantageous if, as described above, strong convection of the melt takes place in the melting unit.

According to one embodiment of the invention, for continuous processing of the melting material, melting material is fed to and discharged from the melting vessel continuously. In particular, the melting material may also be supplied in molten form via an inlet and discharged likewise in molten form via an outlet. This realization of the method, and of a corresponding apparatus, is particularly expedient for the refining of a melt in a continuous production process, since an apparatus which is correspondingly configured as a refining unit can easily be connected downstream of, for example, a melting-down furnace, with the melt being removed from the unit via the outlet after refining.

Moreover, it may be advantageous for the electrodes to be arranged in such a way in the melting unit that the electrodes are positioned opposite one another in the direction of flow or transversely with respect to the direction of flow. If continuous melting is taking place, for example when using the apparatus as a refining unit with a

continuous inflow and outflow, the electrodes can be installed in such a way that the electrical heating current between the electrodes flows substantially in the main direction of flow of the melt or transversely with respect thereto. These two arrangements or directions of current flow are advantageous, inter alia, in order to promote the formation of suitable convection circulation zones in the melt, by means of which the melting material is transported through the melting vessel. It is particularly expedient to form convection circulation which rotates with the axis of rotation perpendicular to the main direction of flow of the melt. Which of the two electrode arrangements, i.e. opposite one another in or perpendicular to the main direction of flow of the melt, is more expedient for the formation of a convection circulation of this nature depends in the individual circumstances on the geometry of the melting vessel. To promote the formation of convection circulation, it is also expedient for the electrodes to be arranged in the lower region of the melting vessel.

In this case, a temperature difference of more than  $150^{\circ}\text{K}$ , preferably more than  $250^{\circ}\text{K}$ , can advantageously be set between the melt-contact surface of the electrodes and a region of the melt located substantially centrally between the electrodes. In this way, convection circulation is set in motion, promoting the transfer of melting material from the inlet to the outlet and passing the melting material through the melting vessel without any short-circuit flow at the melt bath surface.

With this opposite arrangement of the electrodes, the melt, to be refined, no longer has to be introduced into the refining unit from below, but rather can advantageously be introduced into the refining unit and withdrawn again from it from above, in the region of the melt bath surface, via inlet

and outlet. This arrangement is in technical terms significantly simpler to realize than the introduction of the melt from below.

5 The invention is explained in more detail below on the basis of preferred embodiments and with reference to the appended drawings, in which identical reference symbols denote identical or similar parts. In the drawings:

10 Figs 1A to 1C: show views of a first embodiment of the invention,

Fig. 2 shows a diagrammatic cross-sectional view of an electrode,

15 Figs 3A to 3F: diagrammatically depict electrode configurations, melting vessel forms and electrode connections for various embodiments of the invention,

Fig. 4 shows a further embodiment of the apparatus according to the invention,

20 Fig. 5 show measured diagrams of temperatures in the melting unit as a function of the heating current, and

Figs 6A to 6C use diagrammatic cross sections through a melting unit to illustrate method steps of a  
25 starting operation.

Figures 1A to 1C illustrate various views of a first embodiment of an apparatus according to the invention for heating melts. The apparatus is denoted overall by 1. Fig. 1B  
30 shows a view of the apparatus 1 as seen in the direction of arrow B in Fig. 1A. Fig. 1C represents a top view as seen in the direction of arrow C in Fig. 1B. The apparatus 1 comprises a melting vessel 3 designed as a skull crucible. The crucible is produced from tubes 7 through which coolant  
35 is passed in the region of the apparatus for cooling the

vessel. Copper, among other materials, is a suitable material for the tubes, on account of its good thermal conductivity. However, on the other hand the strength of copper is not particularly high, and consequently tubes made from metal with a high mechanical strength or thermal stability, in particular tubes made from high-strength or heat-resistant steel, may also be suitable.

To minimize the heat loss via the skull walls, the walls may moreover be provided with a surface which reflects infrared. By way of example, the tubes 7 may for this purpose be provided with a platinum or gold coating, which may in particular also be polished in order to increase the reflectance. Rhodium, chromium, nickel or palladium, as well as alloys thereof, can also be used for this purpose.

A refractory collar 13, which is preferably made from chemically resistant material, is arranged at the crucible in the region of the melt bath surface, in order to suppress reactions at the three-phase boundary which is formed at the boundary of the melt bath surface with the furnace upper atmosphere. This collar may, for example, comprise a fused-cast ceramic material. An inlet 9 and an outlet 10 with melting-material channels 11, via which the melting material is supplied and discharged continuously in the region of the melt bath surface of the melting vessel, are machined into the refractory collar. Moreover, a bottom outlet 15, through which the crucible can be emptied, is arranged at the base 14 of the melting vessel. Unlike in the embodiment shown in Fig. 1, the skull tubes may also project out of the melt bath surface and be coated with plastic, for example, at least in the region of the melt-bath surface, in order to increase the chemical resistance. A suitable plastic for this purpose is in particular Teflon.

At the side wall of this embodiment of the apparatus 1, two electrodes 5, which have coolant connections 6 as part of a device for cooling the electrodes and via which coolant is passed through passages in the interior of the electrodes, are arranged in corresponding cutouts in the side wall 16 of the melting vessel. On account of the arrangement according to the invention, the electrodes 5 replace part of the side wall 16 of the melting vessel 3, the electrodes 5 moreover being arranged opposite one another at the melting vessel. To keep the current density in the melt-contact material of the electrodes low, the electrodes 5 maintain a large surface area. It is preferable for the electrodes 5 in this case to replace at least 15% of the wall surface area of the melting vessel in the region of the melt.

To heat the melt, a heating current is passed through the melt via the electrodes 5, with the electrodes 5 being insulated with respect to the melting vessel 3, so that no current can flow via the walls of the melting vessel and reduce the heating power. In order nevertheless to maintain resistance to short circuits in the event of a defect in the insulation, it is also possible, moreover, for the wall elements of the melting vessel to be divided into segments that are insulated from one another. Furthermore, the electrodes are arranged on the same sides of the apparatus 1 as inlet 9 and outlet 10 for the melt, so that the heating current between the electrodes flows substantially in the direction of the main direction of flow of the melt or in the opposite direction thereto.

The electrodes are of large-area dimensions, so that the current which emerges from the electrodes into the melt does not exceed a current density of  $5 \text{ A/cm}^2$  at any point on the melt-contact surface. A heating current, preferably with an

alternating current frequency in a range from 50 Hz to 50 kHz, particularly preferably with an alternating current frequency in a range from 2 kHz to 10 kHz, is passed through the melt located in the melting vessel 3 via the electrodes 5 by means of a device for generating alternating current.

Fig. 2 shows a diagrammatic cross-sectional view of an electrode 5. The electrode 5 has electrical supply conductors 52, which are connected to the melt-contact material 53 and can be connected to a power supply, preferably a medium-frequency transformer, for conductive heating of the melt. The melt-contact material 53 of the electrode 5 has a melt-contact surface 51 which is in contact with the melt. To stabilize the melt-contact material 53 in the melt with respect to the hydrostatic pressure of the melt, the melt-contact material 53 is secured to a supporting apparatus 54. The supporting apparatus 54 may be produced, for example, from refractory ceramic. Moreover, in this embodiment the supporting apparatus 54 is also provided with metal holding plates 56 which are used to fit and secure the electrode 5. The metal holding plates secure the electrode to the melting unit or the melting vessel, making it easy to exchange the electrode 5.

The electrode 5 is integrated in a melting or refining unit in such a way that the melt-contact surface 51 forms a wall region of the melting vessel. The melt-contact material 53 is preferably made from refractory metal, such as platinum or a platinum alloy, which has only a low susceptibility to corrosion and migration of electrode material into the melt at temperatures below 1 600°C. A conductive, refractory ceramic, such as for example SnO<sub>2</sub> ceramic, is also suitable for some melts.

The supporting apparatus 54 has a multiplicity of connections 6 which are connected to fluid-carrying passages in the interior of the supporting apparatus 54. A first group of connections 61 is connected to a first cooling circuit, and a second group of connections 62 is connected to a second cooling circuit. The first cooling circuit is preferably an air-cooling circuit, and the second cooling circuit is preferably a water-cooling circuit. The fluid-carrying passages of the first cooling circuit in the interior of the supporting structure 54 are, moreover, arranged in such a way that the coolant comes into direct contact with the melt-contact material on the opposite side from the melt-contact surface 51. These cooling circuits allow the cooling capacities of the electrodes to be controlled or set separately.

Moreover, the electrode has an ohmic heating device. This device comprises a current source 33, which is connected to the melt-contact material 53 via supply conductors 34. For ohmic heating of the electrode 5, therefore, a current can be passed through the melt-contact material 53, which is then heated. This type of heating of the melt-contact material 53 in transverse current mode is particularly advantageous since in this way heating is effected particularly close to the melt, and therefore the heating has only a very low inertia.

Figures 3A to 3F show diagrammatic illustrations of possible electrode configurations, melting-vessel forms and electrode connections of various embodiments of the invention.

Fig. 3A shows a first embodiment of an apparatus which, similarly to the embodiment explained with reference to Figures 1A to 1C, has a melting vessel 3 which is substantially square in terms of its basic contour. The side walls 16 of the melting vessel are in this case each arranged



at right angles to the base, so that the melting vessel 3 is cuboidal in form. The electrodes 501 and 502 are fitted at opposite sides of the melting vessel, so that the heating current has to pass through the melt between the electrodes  
5 in the melting vessel 3 over the entire width of the melting vessel, resulting in a uniform distribution of the heating power in the melt. To heat the melt, the electrodes 501 and 502 are connected to the poles of an alternating current source 18 as a device for generating alternating current and  
10 form an electrode pair.

Furthermore, the electrodes 501 and 502 are arranged in the lower part of the melting vessel, beneath the melt bath surface, in the region of the lower two thirds of the overall  
15 height of the melting vessel. As a result, the electrodes 501, 502 are always completely immersed in the melt, and a three-phase boundary that is critical in terms of corrosion is avoided. Arranging the electrodes in the lower region of the melting vessel moreover increases the size of the region  
20 which is at an elevated temperature compared to the melt-contact surfaces of the electrodes, since the dissipation of heat from the melt-bath surface in the upper part is considerably lower than the dissipation of heat via the walls and electrodes.

25 Fig. 3B illustrates an embodiment of the apparatus with two opposite, obliquely arranged side walls 161 and 162 of the melting vessel. The electrodes 501 and 502 each take up a planar region of these side walls. The oblique arrangement of  
30 the electrodes with respect to one another means that the current covers a longer distance in the upper region of the melting vessel, where the melt is at a higher temperature and consequently has a better conductivity. This causes the ohmic resistances along the different paths to be at least  
35 partially matched to one another, which leads to a more

homogeneous distribution of the heating power in the melt and on the electrode surface.

Fig. 3C shows an embodiment of the apparatus 1 with a plurality of electrode pairs. In each case two of the electrodes 501, 502, 503 and 504, which are arranged on opposite sides of the wall 16, are combined to form an electrode pair which is in each case supplied by an alternating current source 18 or 20. The electrodes 501 and 502 are in this case connected to the alternating current source 18, and the electrodes 503 and 504 are in this case connected to the alternating current source 20.

The electrode configuration of this embodiment is particularly suitable for heating melts with a high electrical conductivity, since independent operation of a plurality of electrode pairs effectively increases the electrode surface area and therefore allows high current densities to be achieved within the melt, in order to achieve sufficient heating powers. However, the electrode pairs have to be arranged in such a way that a shunt connection via electrically conductive wall elements, specifically melting-vessel parts or electrodes, is avoided.

Fig. 3D shows a further embodiment of the apparatus having a plurality of electrode pairs. Unlike the embodiment of the apparatus explained with reference to Fig. 3C, however, in this case the electrodes are not arranged next to one another, but rather above one another. In this case, the two electrodes 501 and 502 form an electrode pair which is supplied by the alternating current source 18 and is arranged closer to the melt bath surface, above the electrodes 503 and 504 which are supplied by the alternating current source 20 and are arranged on the same sides of the melting vessel 3. An arrangement of this type is particularly suitable for

influencing the spatial temperature distribution in the melt by separate operation of the electrode pairs arranged above one another, thereby allowing, for example, the shape and extent of one or more convection circulation zones in the melt to be controlled.

Fig. 3E illustrates an embodiment with an annular electrode 501 and a second electrode 502 in the form of a bottom electrode. The electrode 501 in this case takes up an annular region of the side wall 16 of the cylindrical melting vessel 3 with a circular or oval basic contour. As an alternative to the circular or oval basic contour illustrated, it may also be in the form of a polygon.

Of course, the other embodiments illustrated by way of example may also have one or more bottom electrodes. Bottom electrodes of this type are advantageous, inter alia, for the targeted delivery of the heating power in the lower region of the melting vessel. This ensures an optimum utilization of the volume and/or avoids dead volumes.

The embodiment of the apparatus illustrated in Fig. 3F, like the embodiment shown in Fig. 3E, comprises a cylindrical melting vessel 3 with a circular or oval basic contour. The electrodes 501 and 502 are arranged in the cylindrical side wall and each form a region of the side wall 16, in the form of a ring segment. A cylindrical melting vessel as shown in the embodiments presented in Figures 3E and 3F, has a smaller surface area of the inner wall compared to cuboidal melting vessels, which reduces the dissipation of thermal energy. However, electrodes in the form of ring segments produce very different resistance paths through the melt. This can be compensated for, for example, by the electrodes being divided again, for example into separately operated segments.

Fig. 4 shows as further embodiment of the apparatus 1 according to the invention, which is designed in particular as a continuous melting-down unit. In this embodiment too, the melting vessel 3 is preferably designed as a skull crucible. The electrodes 5 are arranged on opposite sides of the melting vessel 3 and form planar regions of the side wall 16.

A cover 27, in which there is a feeder 30 for adding melting material, is located on the melting vessel 3. The melt is discharged via an outlet 10. Moreover, a gas burner is arranged in the outlet, preventing the melt from cooling as it is discharged through the outlet. In addition, a cooled bridge 26 is arranged between outlet and feeder, in such a way that it is immersed in the melt 22 from above, through the melt bath surface 24. This prevents melting-down material which has not yet been melted from passing directly into the outlet 10, but rather this material remains in the melting vessel 3 for a sufficient length of time. Moreover, a gas burner, by which, for example when starting up, the melt 22 can be preheated to a sufficient temperature for it to have a conductivity sufficient for the conductive heating, is arranged in the upper furnace above the melt bath surface 24. The conductive heating by the electrodes 5 and the simultaneous cooling of the skull walls and the electrodes 5 leads to a temperature drop within the melt from the center region toward the cooled walls. As a result, a hot zone 23, the temperature of which can be set in such a way by the interaction of cooling and heating power that it is more than  $150^{\circ}\text{K}$ , preferably more than  $250^{\circ}\text{K}$ , higher than the temperature of the electrode surfaces, is formed in the center region of the melt 22. As a result, moreover, a strong convection flow is formed in the melt, producing one or more convection circulation zones 25. In this way, the melting

material is passed through the melting vessel, and dead zones, in which the melting material remains in the melting vessel for an excessive length of time, are avoided in the melt 22. Furthermore, the convection can be boosted by a blowing nozzle 32, through which, for example, oxygen or noble gases can be blown into the melt 22.

Fig. 5 shows measured diagrams of temperatures as a function of the heating current. The melting material used was display glass without any alkali metals. The curve illustrated in dotted lines shows the temperature dependency in the hot zone 23 of the melt. The measured curve illustrated by a solid line indicates the temperature measured values at the melt-bath surface 24, and the measurement curve illustrated by dashed lines represents the measured values at the electrode surface.

In this case, cooling with two cooling circuits was used for the electrode. For this purpose, one of the cooling circuits was operated with air as coolant, which comes into direct contact, via fluid-carrying passages, with a plate with a good thermal conductivity, on which the melt-contact material is arranged. The measurement curves demonstrate that the method according to the invention produced a temperature difference of  $242^{\circ}\text{C}$  between hot zone 25 and electrode surface. In this context, the temperature difference can also be increased further, inter alia, by water being added to the cooling air so as to form an aerosol.

Figures 6A to 6C show diagrammatic cross sections through a melting unit 1 to illustrate method steps of a starting operation or of initial operation. Fig. 6A for this purpose shows the starting state, in which the melting vessel 3 of the melting unit 1 has been filled with solid melting material 35. The melting material 35 may be added, for

example, in the form of charge cullet or batch.

Next, as shown in Fig. 6B, starting electrodes 37 and 39 are introduced into the melting material. The starting electrodes  
5 37 and 39 are connected to a current source or power supply 41. Then, a small region of the melting material, for example at the surface, is heated between the electrodes 37 and 39 by means of a fossil burner until the conductivity of this small region is sufficient for conductive heating via the starting  
10 electrodes. Next, the conductive heating between the electrodes 37 and 39 forms a molten region 220. The electrodes 37, 39 can slowly be moved apart, correspondingly increasing the size of the region 220 between them.

15 At the same time, the electrodes 51 and 52 which are integrated in the wall of the melting vessel 3 can be preheated. This is effected by means of in each case one power supply 33 connected to the melt-contact material of the electrodes, effecting a transverse current mode and therefore  
20 ohmic heating of the melt-contact material. The walls of the melting vessel 3, on the side facing the melt, can additionally be lined with a material of poor electrical and thermal conductivity, for example with ceramic plates or  $\text{SiO}_2$  slip.

25 The transverse current mode also causes melting material to be melted in the region of the electrodes, forming molten regions 221 and 222. When the starting electrodes have been moved so far apart that they reach the vicinity of the  
30 electrodes 51 and 52, the molten regions 221 and 222 finally in each case come into contact with the molten region 220. This produces a molten region which extends from one of the electrodes 51 and 52 to the other, thereby forming a conductive bridge. After that, the power supply 18 for the  
35 two electrodes 51 and 52 can start to operate, and in this

way the melt can be heated with a high power by means of these electrodes.

List of reference symbols

1	Apparatus for heating a melt
3	Melting vessel
51, 501, 502	Electrode
51	Melt-contact surface of the electrode 5
52	Electrical supply conductors
53	Melt-contact material of the electrode 5
54	Supporting structure for melt-contact material 53
46	Metal holding plate
6	Coolant connections
61	Connections for the first cooling circuit
62	Connections for the second cooling circuit
7	Tubes of the skull crucible
9	Inlet
10	Outlet
11	Melting material channel
13	Refractory collar
14	Base of the melting vessel
15	Bottom outlet
16	Side wall of the melting vessel 3
161, 162	Obliquely positioned side walls of the melting vessel 3
18, 20, 33	Alternating current source
22	Melt
220, 221, 222	Molten regions
23	Hot region
24	Melt bath surface
25	Convection circulation
26	Bridge
27	Cover
28, 29	Gas burner
30	Feeder
32	Blowing nozzle
34	Supply conductors



- 35 Solid melting material
- 37, 39 Starting electrodes
- 41 Power supply for starting electrodes 37, 39